Chemical cotton stalk destruction for maintenance of host-free periods for the control of overwintering boll weevil in tropical and subtropical climates†‡

Shoil M Greenberg,[1*] Alton N Sparks Jr,[2] John W Norman Jr,[2] Randy Coleman,[3] Joe M Bradford,[3] Chenghai Yang,[3] Thomas W Sappington[1] and Allan Showler[1]

[1]USDA, ARS, Areawide Pest Management Research Unit, Weslaco, TX 78596, USA
[2]Texas Agricultural Research and Extension Center, Texas A&M University, Weslaco, TX 78596, USA
[3]USDA, ARS, Kika de la Garza Subtropical Agricultural Research Center, Weslaco, TX 78596, USA

Abstract: In the Lower Rio Grande Valley (LRGV) of Texas, cotton regrows and produces fruit from undestroyed stalks throughout the winter, and in spring weevils from such locations become a serious threat. The success of the boll weevil eradication program, which was reintroduced in the LRGV in 2005, will be dependent on thorough stalk destruction following harvest. However, adverse weather conditions and conservation tillage often impede immediate and complete stalk destruction using typical tool implements, and alternative stalk control methods are needed. This study provides an examination of the efficacy for cotton stalk destruction of different herbicides (thifensulfuron-methyl + tribenuron-methyl, dicamba-diolamine, 2,4-D-dimethylammonium, flumioxazin, 2,4-DB-dimethylammonium and carfentrazone-ethyl) and their rates, spray volumes and application timings on shredded or standing cotton stalks after stripper or picker harvest. None of the tested herbicides, except 2,4-D-dimethylammonium, stopped post-harvest cotton regrowth and fruiting. 2,4-D-dimethylammonium sprayed once (0 or 7 days) after cotton was harvested at 1 lb AE acre^{-1} (1.12 kg ha^{-1}), in a spray volume of 10 gal water acre^{-1} (93.5 L ha^{-1}) with 5 mL L^{-1} surfactant, was highly effective in stalk destruction (72–90%). The best results were achieved when the herbicide was applied immediately after the cotton was shredded, followed by standing stripper-harvested and standing picker-harvested cotton. 2,4-D-dimethylammonium applied twice, 0 and 14 (or 21) days after cotton harvest, was 100% effective in killing stalks, regardless of whether they were shredded or standing, or whether harvest was by stripper or picker. These findings showed that 2,4-D-dimethylammonium cotton stalk destruction eliminated food and reproductive opportunities for managing overwintering boll weevils [*Anthonomus grandis grandis* Boheman (Coleoptera: Curculionidae)].
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Keywords: boll weevil; herbicides; cotton regrowth; stalk destruction; stripper and picker harvest; 2,4-D

1 INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is a perennial shrub that may survive for many years in a favorable environment. The perennial nature of cotton allows it to regrow following harvest, producing fruit suitable for boll weevil (*Anthonomus grandis grandis* Boheman) reproduction in 3–4 weeks. This regrowth potential is of little concern in areas where winter weather kills cotton and prevents boll weevil reproduction, but represents a severe challenge to boll weevil management in tropical and subtropical regions. Cotton stalk destruction is a primary tool for managing overwintering boll weevils in these regions, including the Lower Rio Grande Valley (LRGV) of Texas, by reducing or eliminating food and reproductive opportunities. Early destruction of cotton stalks by plowing or burning was among the initial and most significant recommendations for control of boll weevil.[1–8] In the LRGV of Texas, weevils can survive during the winter in bolls of undestroyed stalks in scattered cotton fields. Cotton in these unattended fields produces fruit throughout the winter, and in the spring weevils from such locations become a serious threat.[9–11]

Mechanical control continues to be a significant means for destroying stalks. Stalks are typically shredded after harvest to reduce stalk size so that plows can easily kill the roots. After shredding, a disk is often used to flatten beds to allow deep tillage operations for breaking hardpan. Stubble stalk pullers also are used to uproot the stalks.[12] These mechanical methods are generally successful, but some stalks may survive

* Correspondence to: Shoil M Greenberg, USDA, ARS, APMRU, 2413 E HWY 83, Bldg 201, Weslaco, TX 78596, USA
E-mail: sgreenberg@weslaco.ars.usda.gov

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these operations. However, LRGV cotton producers are increasingly adopting conservation tillage, a system antithetical to mechanical operations. Adverse weather conditions can also impede immediate and complete stalk destruction using typical tool implements. Thus, there is a need for alternative stalk control methods. Studies of selected herbicides for stalk destruction were started in the LRGV in 2001.[13,14] Similar experiments have been conducted in the Coastal Bend, Upper Gulf Coast and Blacklands regions of Texas.[15,16] Remote sensing technology is being used to evaluate cotton regrowth control as an alternative to traditional visual observations and ground measurements.[17,18]

The original purpose of this study was to find a chemical means by which cotton producers who were using conservation tillage practices could destroy stalks without plowing the fields. The success of the boll weevil eradication program, which was reintroduced in the LRGV in 2005, will be dependent on thorough stalk destruction following harvest. It is anticipated that effective cotton stalk destruction in the LRGV can be achieved by chemical crop termination. Producers' attempts at chemical stalk control have relied heavily on herbicides containing 2,4-D, and have had variable degrees of success, which may be influenced by both harvest and post-harvest activities. Potential harvest and post-harvest practices that may influence chemical stalk destruction include the type of harvester used (picker versus stripper harvest), whether stalks are shredded after harvest or not and whether herbicides are applied immediately after harvest or after a period of cotton regrowth. Before the present study, information about herbicide effects on shredded and standing cotton stalks was absent.

The objective of the present study was to evaluate the efficacy of selected herbicides and their rates, spray volumes and application timings on shredded and standing cotton stalks after stripper and picker harvest in the LRGV.

2 MATERIALS AND METHODS

The experiments were conducted in the greenhouse and field plots of USDA-ARS-APMRU, South and North Farms, Weslaco, Texas, and the Texas A&M Research and Extension Center's Hiler Farm, Weslaco, Texas, during 2001–2004.

2.1 Herbicides tested

The various herbicides for these studies were selected on the basis of their potential ability to destroy cotton (farmers' and manufacturers' suggestions), but no evidence for actual stalk destruction had been gathered (Table 1).

2.2 Experimental design

2.2.1 Greenhouse tests

Cotton (DPL 5415 RR) plants were grown in 2.5 gal (9.5 L) pots with 3–4 plants per pot. When bolls started to open, the plants were cut off at 15–20 cm from the soil line to simulate shredding.

Five pots assigned to each treatment were aligned to simulate a row of cotton, which was sprayed with a given herbicide using a carbon dioxide pressurized (40 psi = 2.76 MPa) backpack sprayer with three TX10 hollow cone nozzles at a total volume of 10 gal acre^{-1} (93.5 L ha^{-1}). After treatment, the plants were held outdoors and watered twice per week.

In 2001, five treatments were evaluated: thifensulfuron methyl + tribenuron-methyl WG at 0.4 and 0.6 oz AI acre^{-1} (28 and 42 g ha^{-1}), sprayed immediately after cotton was shredded; 2,4-DB-dimethylammonium SL at 1.0 and 2.0 lb AE acre^{-1} (1.12 and 2.24 kg ha^{-1}), sprayed immediately after cotton was shredded; and control (sprayed with water immediately after cotton was shredded). Each treatment was replicated 3 times.

In 2002, seven treatments were evaluated: 2,4-D-dimethylammonium SP at 1.0 lb AE acre^{-1} (1.12 kg ha^{-1}), sprayed immediately (0 days) and 7 or 14 days after cotton was shredded; dicamba-diolamine SL at 2.0 oz AE acre^{-1} (140 g ha^{-1}), sprayed immediately (0 days) and 7 or 14 days after cotton was shredded; and an untreated control. Each treatment was replicated 3 times.

2.2.2 Small field plot tests

In 2001, experiments were conducted at the Texas Agricultural Experiment Station's Hiler Farm, near Weslaco, Texas, in two irrigated fields. Cotton (SureGrow 125) was planted on 20 February, and harvested on 23 July in both fields. Half of each field was shredded, with a two-row rotary shredder, immediately after cotton was picker harvested, and the other half was left as non-shredded (standing)

Table 1. Herbicides tested for their ability to provide cotton stalk destruction for control of overwintering boll weevil

Brand name	Active ingredient	Formulation type	Content	Producer
Savage®	2,4-D-dimethylammonium	SP	785 g AE kg^{-1}	Loveland Products Inc., Greeley, CO
Butoxone® 200	2,4-DP-dimethylammonium	SL	240 g AE L^{-1}	Cedar Chemical Corporation, Memphis TN
Clarity®	Dicamba-diolamine	SL	480 g AE L^{-1}	BASF Agricultural Products Group, NC
Harmony® Extra	Thifensulfuron-methyl + tribenuron-methyl	WG	500 + 250 g kg^{-1}	DuPont de Nemours and Company, Wilmington, DE
Valor™	Flumioxazin	WG	500 g kg^{-1}	Valent, Walnut Creek, CA
Aim™	Carfentrazone-ethyl:	EC	240 g l^{-1}	FMC Corporation, Philadelphia, PA
Roundup™	Glyphosate-isopropylammonium	SL	360 g AE L^{-1}	Monsanto Co., St Louis, MO

cotton stalks. Two herbicides were tested, 2,4-D-dimethylammonium SP and thifensulfuron-methyl + tribenuron-methyl WG, with one herbicide used in each field. Each herbicide test consisted of a factorial arrangement of the following application factors: two herbicide rates [1.0 and 2.0 lb AE acre^{-1} (1.12 and 2.24 kg ha^{-1}) for 2,4-D-dimethylammonium, and 0.4 and 0.6 oz AI acre^{-1} (28 and 42 g ha^{-1}) for thifensulfuron-methyl + tribenuron-methyl]; three application timings and two post-harvest stalk conditions [sprayed immediately (0 days) and 7 or 14 days after cotton was harvested and shredded or applications to standing picker-harvested cotton stalks at 0, 7 or 14 days after harvest; two spray volumes {low volume of water [8.18 or 8.54 gal acre^{-1} (76.5 or 79.9 L ha^{-1})] and high volume [13.9 or 14.2 gal acre^{-1} (130 or 133 L ha^{-1})]}; and untreated control. Each treatment was replicated 4 times in a randomized block design. Each plot consisted of four 40 inch (1.02 m) rows with a length of 40 ft (12.2 m). Plots were separated at the end of the rows by 15 ft (4.6 m) alleys, and across the rows by two rows of standing cotton stalks. All applications were made with a compressed air pressurized sprayer mounted on a spider track sprayer (West Texas Lee Co., Inc., Idalou, TX) with three hollow cone nozzles per row. For low-volume applications, No. 23 cores with D3 tips were used, and for high-volume applications, No. 25 cores with D5 tips were used.

In 2002, experiments were conducted in an irrigated field at the USDA-ARS-APMRU South Farm at Weslaco, Texas. Cotton (DPL-5415 RR) was planted on 22 February and picker harvested and shredded by a rotary shredder on 25 July 25. Four herbicides were tested at a single rate each: 2,4-D-dimethylammonium SP at 1.0 lb AE acre^{-1} (1.12 kg ha^{-1}) + 5 mL L^{-1} surfactant; dicamba-diolamine SL at 2.0 oz AE acre^{-1} (140 g ha^{-1}); flumioxazin WG at 0.5 oz AI acre^{-1} (35 g ha^{-1}) + glyphosate SL at 1 lb AE acre^{-1} (1.12 kg ha^{-1}); thifensulfuron-methyl + tribenuron-methyl WG at 0.4 oz AI acre^{-1} (14.0 g ha^{-1}); and untreated control. Chemicals were sprayed 0, 7 and 14 days after cotton was harvested and shredded with a calibrated spider track sprayer with two nozzles on drops and one nozzle (TurboTeeJet-11 002) over the top of each row (12 gal acre^{-1} = 112 L ha^{-1}). Each treatment was replicated 3 times in a randomized block design. Each plot consisted of four rows on 40 inch centers (1.02 m) by 148 ft (45.0 m). Plots were separated across the rows by two rows of standing cotton stalks.

In 2003, all field plot experiments were conducted in irrigated fields at the USDA-ARS South Farm at Weslaco, Texas. Cotton (DPL-5415 RR) was planted on 28 February in one field, and on 4 March in the second field. Cotton in the first field was picker harvested and shredded on 22 July. Herbicide treatments were applied with the spider track sprayer at one rate each: 2,4-D-dimethylammonium SP alone at 1.0 lb AE acre^{-1} (1.12 kg ha^{-1}), sprayed once at 0 and 7 days, and twice at 0 and 14 days and at 0 and 21 days after cotton was harvested and shredded; 2,4-D-dimethylammonium at 1.0 lb AE acre^{-1} (1.12 kg ha^{-1}) in combination with carfentrazone-ethyl EC at 0.75 oz AI acre^{-1} (52.5 g ha^{-1}), sprayed once at 7 days after shredding, and twice at 0 and 7 days and at 0 and 14 days after cotton was harvested and shredded; and dicamba-diolamine SL at 0.5 lb AE acre^{-1} (0.56 kg ha^{-1}), sprayed once at 0 and 7 days after shredding, and twice at 0 and 21 days or 7 and 21 days after cotton was harvested and shredded. An untreated control was included for comparison. Herbicides were applied in 10 gal water acre^{-1} (93 L ha^{-1}) with the spider track sprayer. Each treatment was replicated 3 times in a randomized block design.

The second field was harvested on 30 July. Ninety-two rows on 40 inch (100 cm) centers by 148 ft (45 m) long were harvested by a stripper, and 92 rows were harvested by a picker. In each stripper- and picker-harvested portion, 46 of the rows were shredded on 31 July, and the other 46 rows were left standing. 2,4-D-dimethylammonium at 1.0 lb AE acre^{-1} (1.12 kg ha^{-1}) was applied once (0 days) or twice (0 and 21 days) after cotton was harvested on both the shredded and standing cotton stalks after stripper and picker harvest. The plot distribution in the field was in a randomized block design. Each treatment was replicated 3 times.

In 2004, field plot experiments were conducted in two irrigated fields at the USDA-ARS South Farm at Weslaco, Texas. Three acres of Bollgard II cotton were planted on 28 February, and two acres of DPL-5415 RR were planted on 1 March. Other experiments were conducted at the North Farm in one irrigated field (1.5 acres = 0.607 ha) planted with Bollgard II cotton on 20 March. The two fields at the South Farm were harvested by a stripper and a picker on 21 July in a randomized block design.

There were 27 plots laid out in three blocks of nine treatments: (1) picker-harvested standing cotton; (2) picker-harvested standing cotton sprayed with 2,4-D-dimethylammonium immediately (0 days) after cotton was harvested; (3) picker-harvested standing cotton sprayed twice with 2,4-D-dimethylammonium at 0 and 14 days post-harvest; (4) stripper-harvested standing cotton; (5) stripper-harvested standing cotton sprayed with 2,4-D-dimethylammonium immediately (0 days) after harvest; (6) stripper-harvested standing cotton sprayed with 2,4-D-dimethylammonium twice at 0 and 14 days post-harvest; (7) cotton shredded immediately after stripper harvest; (8) cotton shredded and sprayed with 2,4-D-dimethylammonium immediately after stripper harvest; (9) cotton shredded and sprayed with 2,4-D-dimethylammonium twice at 0 and 14 days after stripper harvest. 2,4-D-dimethylammonium SP was applied at 1.0 lb AE acre^{-1} (1.12 kg ha^{-1}) in all treatments.

The North Farm cotton field was not harvested, but only shredded on 26 July when about 50% of the bolls were opened. Half of the field was sprayed with 2,4-D-dimethylammonium at 1.0 lb AE acre^{-1}

immediately after shredding, and the other half was sprayed with 2,4-D-dimethylammonium twice, at 0 and 14 days post-shredding.

In all years, standard cotton production practices were used in all experimental plots. Before cotton was harvested, when ≈50% of the bolls were opened, the fields were sprayed with tribufos 0.235 kg ha^{-1} + thidiazuron 0.125 kg ha^{-1} + azinphos-methyl 0.140 kg ha^{-1} for defoliation and to reduce the number of overwintering boll weevils.[19]

2.3 Experimental indices and their assessment

2.3.1 Greenhouse tests

In both greenhouse tests, plants were evaluated at 1 and 2 months after treatment. Evaluations included plant height, number of leaves per plant and number of fruiting structures per plant. These growth parameters were recorded on all treated plants and untreated control. The growth parameters determined the level of regrowth of cotton (or its mortality), ranging from no regrowth of cotton (100% mortality) to high regrowth of cotton (regrowth parameters equaling 80% or more compared with the untreated control), but this was a subjective evaluation.

Because the herbicides used deformed cotton fruit (squares and bolls), the number of deformed squares (from all available), the ability of boll weevil females to feed and lay eggs on them and the number of weevils that completed their development to the adult stage within infested squares compared with untreated normal squares (control) were recorded. Mated females by the end of the conditioning period were assigned to untreated normal squares (7–9 mm diameter at the widest part of the flower bud and with bracteoles intact) and deformed squares after spraying plants with the herbicides. There were ten replications (females) per treatment. Each female was isolated in a 15 cm diameter ventilated petri dish and placed in an environmental chamber at 25 ± 1 °C, 65% RH, and a 12:12 h light:dark photoperiod. Each female was provided with three squares, which were replaced daily for the first 10 days after onset of oviposition, after which the experiment was terminated. The oviposition (sealed) punctures were counted under a dissecting microscope daily. The number of sealed punctures is a relative estimate of the number of eggs oviposited.[20] Infested squares were placed in an environmental chamber to optimize development of immature weevils to the adult stage.

2.3.2 Small field plot tests

Each plot was visually rated on a weekly basis until termination of the experiment. Although the Texas Department of Agriculture approved requests for stalk destruction deadline extensions for these studies, it was agreed that individual treatments would be eliminated prior to production of fruiting structures. Thus, the extensions granted allowed for thorough evaluation of stalk destruction and potential survival, while individual treatment termination at first squaring prevented reproduction by boll weevils. Plants were rated on a 1–5 scale as follows: 1, no live plants; 2, ≤25% plants alive, but exhibiting herbicide injury; 3, 25–50% plants alive, but exhibiting herbicide injury; 4, 50–75% plants alive, but exhibiting herbicide injury; 5, ≥75% plants alive, and not exhibiting herbicide injury. For evaluation of field plant damage, use was made of ten randomized sites per 1 m in each replication. Before the plants were destroyed, root mortality and number of fruiting plants per treatment were determined. Root mortality evaluations were made by pulling out cotton plants within a 1 m row segment from ten randomly selected sites in each plot, cleaning the epidermis of the roots and determining whether roots were dead or alive. Brown-colored, dry and easily broken roots were considered to be dead. About 100 randomly selected plants per treatment were examined for the presence of fruit.

Ground reflectance spectra and airborne multispectral digital imagery data were collected from the experimental plots during the 2002–2003 growing seasons. Spectral variables including green, red and near-infrared (NIR) bands of the airborne multispectral imagery and vegetation indices derived from the three bands were used to compare the differences among the treatments.

2.4 Statistical analyses

Use was made of one-way analysis of variance (ANOVA) tests to examine differences among three or more treatments. Whenever significant F values were obtained, means were separated using Tukey's studentized range test. For comparing the experiments with two treatments, use was made of the t-test ($\alpha = 0.05$).[21] Percentage data were arcsine-square root transformed before statistical analysis to stabilize variances,[22] but are presented as non-transformed means.

3 RESULTS AND DISCUSSION

3.1 Greenhouse tests

All herbicides tested showed a negative effect on cotton growth, and the formation of fruit at 1 and 2 months after treatment, compared with the untreated control (Table 2). Thifensulfuron-methyl + tribenuron-methyl sprayed immediately (0 days) after cotton was shredded, dicamba-diolamine sprayed 7 and 14 days after cotton was shredded and 2,4-D-dimethylammonium sprayed 14 days after cotton was shredded had little effect on cotton growth. By contrast, 2,4-DB-dimethylammonium and dicamba-diolamine sprayed immediately (0 days) after cotton was shredded and 2,4-D-dimethylammonium sprayed 0 and 7 days after cotton was shredded had a much greater impact on plant growth. The average number of leaves per plant treated with thifensulfuron-methyl + tribenuron-methyl (0 days after cotton was shredded, 28 and 42 g ha^{-1}, and 1 month after treatments) decreased by 25.5%

Table 2. Plant growth parameters (±SE) of regrowth cotton in greenhouse experiments after simulated post-shredding treatment with indicated herbicides[a]

Treatment[b]	One month after treatment: Number of leaves per plant	One month after treatment: Plant height (cm)	One month after treatment: Fruit per plant	Two months after treatment: Number of leaves per plant	Two months after treatment: Plant height (cm)	Two months after treatment: Fruit per plant
USDA-ARS, South Farm, Weslaco, Texas, 2001						
Control	21.6 (±2.1) a	59.0 (±4.7) a	2.8 (±0.8) b	21.1 (±6.2) a	55.6 (±8.9) a	1.0 (±0.2) a
Thifensulfuron-methyl + tribenuron-methyl, 28 g ha^{-1}	17.8 (±1.2) b	39.4 (±3.2) b	4.1 (±1.5) a	18.7 (±3.2) ab	40.6 (±5.8) b	1.1 (±0.2) a
Thifensulfuron-methyl + tribenuron-methyl, 42 g ha^{-1}	14.3 (±1.2) b	37.0 (±2.4) b	3.2 (±1.0) ab	16.0 (±3.3) b	37.1 (±6.4) b	0.6 (±0.2) a
2.4-DB, 1.12 kg AE ha^{-1}	2.7 (±0.9) c	29.9 (±2.6) c	0 c	0.5 (±0.5) c	29.8 (±3.7) c	0 b
2.4-DB, 2.24 kg AE ha^{-1}	3.7 (±1.0) c	28.5 (±2.9) c	0 c	1.1 (±1.0) c	28.8 (±4.5) c	0 b
ANOVA	$F = 818.4$	$F = 346.1$	$F = 90.0$	$F = 148.8$	$F = 73.2$	$F = 11.0$
	df = 4, 109	df = 4, 109	df = 4, 107	df = 4, 109	df = 4, 107	df = 4, 105
	$P = 0.001$	$P = 0.001$	$P = 0.001$	$P = 0.001$	$P = 0.001$	$P = 0.001$
USDA-ARS, South Farm, Weslaco, Texas, 2002						
Control	19.4 (±1.5) a	27.3 (±1.0) a	1.0 (±0.3) a	27.6 (±1.4) a	38.4 (±1.3) a	5.0 (±0.6) a
2.4-D (0 days)	3.4 (±1.1) c	19.7 (±0.7) b	0 b	7.0 (±1.4) d	23.0 (±0.9) c	0 c
2.4-D (7 days)	5.1 (±0.8) c	22.8 (±0.5) b	0 b	5.0 (±1.7) d	21.7 (±0.7) c	0 c
2.4-D (14 days)	12.9 (±0.9) b	22.3 (±0.5) b	0 b	13.0 (±0.7) c	24.8 (±0.6) c	0.4 (±0.2) b
Dicamba (0 d)	7.5 (±1.0) c	24.0 (±0.4) b	0 b	7.8 (±2.5) d	24.1 (±0.7) c	0.8 (±0.3) b
Dicamba (7 days)	14.2 (±1.4) b	22.3 (±0.6) b	0 b	14.9 (±1.9) c	28.9 (±1.7) b	0.7 (±0.2) b
Dicamba (14 days)	14.0 (±1.2) b	23.8 (±0.5) b	0 b	18.0 (±1.6) b	26.4 (±0.5) bc	3.9 (±0.9) a
ANOVA	$F = 23.8$	$F = 13.8$	$F = 9.7$	$F = 24.6$	$F = 32.1$	$F = 21.7$
	df = 6, 154	df = 6, 154	df = 6, 154	df = 6, 154	df = 6, 154	df = 6, 154
	$P = 0.034$	$P = 0.001$	$P = 0.001$	$P = 0.001$	$P = 0.001$	$P = 0.001$

[a] Means within a column followed by the same letter are not significantly different (Tukey honestly significant difference, $P \leq 0.05$).
[b] Numbers in parentheses indicate days post-shredding when herbicide was applied.

compared with the untreated control. The average number of leaves per plant treated with dicamba-diolamine 0 days after cotton was shredded, with 2,4-D-dimethylammonium 0 and 7 days after cotton was shredded and with 2,4-DB-dimethylammonium 0 days after cotton was shredded and 1 month after treatments decreased by 61.3, 82.5, 73.7 and 85.2% respectively compared with the untreated control. The true target of these treatments was to prevent cotton from fruiting, thus preventing any potential reproduction by boll weevils. Only 2,4-DB-dimethylammonium, sprayed 0 days after cotton was shredded, and 2,4-D-dimethylammonium, sprayed 0 and 7 days after cotton was shredded, prevented fruiting through 2 months post-treatment, while spraying with dicamba-diolamine 0 days after shredding prevented fruiting only through the first month after treatment. Although many of the treatments did not prevent fruiting, most of the fruits from the plants treated with herbicides were deformed compared with the untreated control ($70.0 \pm 5.8\%$ versus $3.3 \pm 3.0\%$; $t = 10.0$, df = 1, $P = 0.001$). If deformed fruit prevented boll weevil reproduction, these treatments could be considered successful. However, the experiments performed with this deformed fruit showed that the percentage of deformed squares with boll weevil egg punctures was not significantly different from the percentage of normal squares ($80.0 \pm 5.7\%$ versus $96.7 \pm 3.3\%$; $t = 2.5$, df = 1, $P = 0.1$). Further, the survival of weevils from deformed and undeformed squares also was not significantly different ($75.2 \pm 6.3\%$ versus $79.6 \pm 5.4\%$; $t = 0.5$, df = 1, $P = 0.6$). Thus, production of any squares would indicate an unsuccessful treatment. No significant effect on cotton growth parameters and fruiting was observed between different rates in treatment with thifensulfuron-methyl + tribenuron-methyl (28 and 42 g ha^{-1}) and treatment with 2,4-DB (1.12 and 2.24 kg AE ha^{-1}) (Table 2).

3.2 Small field plot tests

In the first field experiments, there was no significant effect of different application rates of 2,4-D-dimethylammonium (1.12 or 2.24 kg AE ha^{-1}) or thifensulfuron-methyl + tribenuron-methyl (28 or 42 g ha^{-1}). Most plants sprayed with 2,4-D-dimethylammonium at 1.12 kg AE ha^{-1} were visually rated as 2.3 ± 0.1, while those treated at 2.24 kg ha^{-1} were rated as 2.4 ± 0.1 ($t = 0.3$, df = 38, $P = 0.752$). Most plants sprayed with thifensulfuron-methyl + tribenuron-methyl at 28 g ha^{-1} were visually rated as 3.1 ± 0.2, while those treated at 42 g ha^{-1} were rated as 3.3 ± 0.2 ($t = 0.5$, df = 28, $P = 0.618$). Furthermore, no significant effect was detected between the two spray volumes (low volume of water, 76.5 or 79.7 L ha^{-1}, and high volume, 130 or 133 L ha^{-1}) with 2,4-D-dimethylammonium at 1.12 kg AE ha^{-1}

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($t = 1.7$, df $= 28$, $P = 0.1$) or with thifensulfuron-methyl + tribenuron-methyl at 28 g ha^{-1} ($t = 0.4$, df $= 28$, $P = 0.704$).

In the treatments with 2,4-D-dimethylammonium sprayed immediately (0 days) or 7 days after cotton was harvested (2001 tests), plant ratings were significantly lower for shredded cotton than for standing picker-harvested cotton ($t = 6.3$, df $= 18$, $P = 0.001$ and $t = 5.2$, df $= 18$, $P = 0.001$ respectively). When cotton was sprayed with 2,4-D-dimethylammonium at 14 days after harvest, there was no significant difference between shredded and standing cotton ($t = 1.5$, df $= 18$, $P = 0.15$) (Table 3).

Standing cotton produced squares on all three 2,4-D-dimethylammonium treatments, but shredded cotton produced squares only under the late spray treatment (14 days after cotton was harvested). The best results with thifensulfuron-methyl + tribenuron-methyl were obtained in the plots that had been shredded and allowed to regrow for 14 days prior to application, but even these plots contained numerous squares (Table 3).

In 2002, 1 month after the experiment was initiated, most plants appeared healthy by visual ratings (rating 5) in the untreated control, as well as in the flumioxazin + glyphosate treatments (Fig. 1A). In the treatment with 2,4-D-dimethylammonium applied 0 days after harvest (DAH) on immediately shredded cotton, the visual rating was 2 (only some plants were alive but appeared unhealthy), with significantly higher cotton mortality than in other treatments. In the 2,4-D-dimethylammonium 7 DAH and dicamba-diolamine 0 and 7 DAH treatments, the visual rating was near 3, and these treatments exhibited significantly higher

Table 3. Effects (±SE) of different chemical treatments and timing of applications on post-harvest cotton stalk destruction (field tests, 2001)[a]

	Standing cotton		Shredded cotton	
Treatment[b]	Plant ratings	Fruit per plant	Plant ratings	Fruit per plant
2,4-D (0 days)	2.1 (±0.1) dA	0.1 (±0.06) bA	1.3 (±0.1) eB	0 bA
2,4-D (7 days)	2.3 (±0.1) dA	0.4 (±0.02) bA	1.4 (±0.1) eB	0 bB
2,4-D (14 days)	3.0 (±0.2) cA	0.3 (±0.02) bA	2.5 (±0.1) dA	0.25 (±0.01) bA
Thifensulfuron-methyl + tribenuron-methyl (0 days)	3.7 (±0.2) bA	3.5 (±0.4) aB	4.1 (±0.2) bA	4.4 (±0.9) aA
Thifensulfuron-methyl + tribenuron-methyl (7 days)	3.7 (±0.1) bA	4.3 (±0.3) aA	4.0 (±0.2) bA	5.2 (±0.5) aA
Thifensulfuron-methyl + tribenuron-methyl (14 days)	3.4 (±0.3) bcA	3.7 (±0.5) aA	3.2 (±0.1) cB	1.7 (±0.2) aB
Control	4.8 (±0.1) aA	4.1 (±0.3) aA	4.6 (±0.1) aA	4.4 (±0.3) aA
ANOVA	$F = 73.9$	$F = 35.2$	$F = 93.2$	$F = 48.0$
	df = 6, 43	df = 6, 113	df = 6, 43	df = 6, 113
	$P = 0.001$	$P = 0.001$	$P = 0.001$	$P = 0.001$

[a] Means within a column followed by the same lower-case letter (Tukey honestly significant difference, $P < 0.05$) and within the row (plant rating and fruit per plant were compared separately between standing and shredded cotton) by the same upper-case letter (t-test) are not significantly different.
[b] Days after harvest in parentheses.

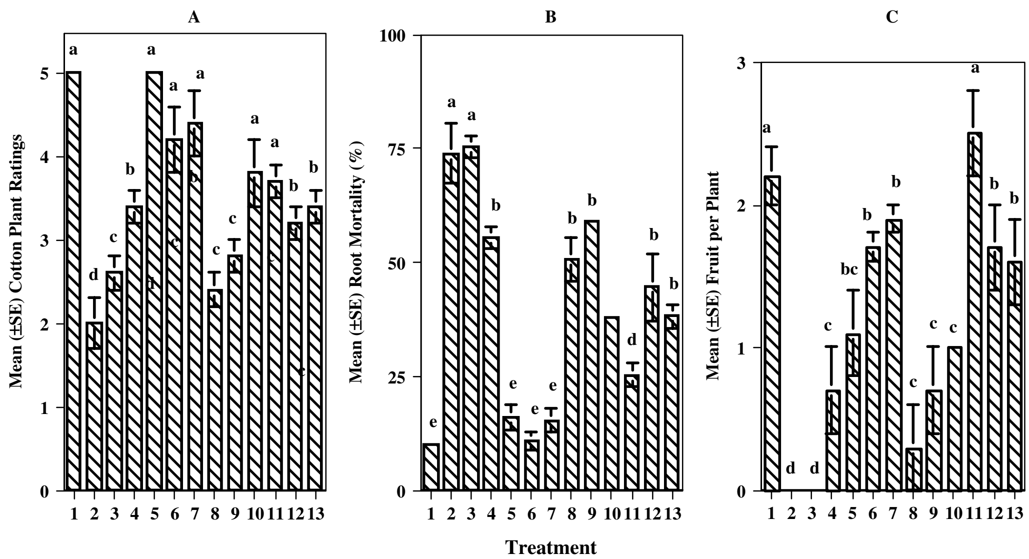

Figure 1. Effects of different herbicides and application timings (days after shredding) on cotton stalk termination in field plots. Different letters on the bars indicate significant differences, Tukey HSD ($P \leq 0.05$) (2002): **A** indexed by visual plant ratings 1–5 (1 = no plants alive, 5 = most plants appear healthy); **B** indexed by root mortality in field plots of regrowth cotton 2 months after treatment; **C** indexed by fruit per plant in field plots of regrowth cotton; **1** control; **2** 2,4-D (0 days); **3** 2,4-D (7 days); **4** 2,4-D (14 days); **5** flumioxazin (0 days); **6** flumioxazin (7 days); **7** flumioxazin (14 days); **8** dicamba (0 days); **9** dicamba (7 days); **10** dicamba (14 days); **11** thifensulfuron-methyl + tribenuron-methyl (0 days); **12** thifensulfuron-methyl + tribenuron-methyl (7 days); **13** thifensulfuron-methyl + tribenuron-methyl (14 days).

efficacy than in the same herbicides applied 14 days after harvest. Thifensulfuron-methyl + tribenuron-methyl showed significantly lower efficacy than 2,4-D-dimethylammonium and dicamba-diolamine. The condition of the plants treated with thifensulfuron-methyl + tribenuron-methyl was rated between 3 and 4. Thifensulfuron-methyl + tribenuron-methyl performed somewhat better when applied after shredded cotton started regrowth (on 7 and 14 DAH) ($F = 26.8$, df $= 12$, 187, $P = 0.001$ for the overall tests in Fig. 1A). The highest plant mortality with 2,4-D-dimethylammonium and dicamba-diolamine was achieved when they were applied soon after shredding, while thifensulfuron-methyl + tribenuron-methyl performed better after regrowth occurred. It is assumed that application of 2,4-D-dimethylammonium and dicamba-diolamine on plant tissue freshly damaged by shredding allowed active uptake of these products. Once the wounds healed, product uptake and performance were reduced. Thifensulfuron-methyl + tribenuron-methyl penetrates through leaf tissue and therefore performed best after plants had sufficient time to regrow, allowing for increased leaf area for uptake of this product.

One month after herbicide treatment of shredded cotton, no significant differences were observed in root mortality ($F = 1.6$, df $= 12$, 26, $P = 0.146$), but differences between treatments were significant after 2 months ($F = 38.6$, df $= 12$, 26, $P = 0.001$) (Fig. 1B). The highest percentage of root mortality was observed in treatments where cotton was sprayed with 2,4-D-dimethylammonium immediately or 7 days after cotton was harvested and shredded, and the lowest percentage was observed in the untreated control and in all three treatments with flumioxazin. Herbicide treatment had a significant effect on fruit production by 2 months post-harvest ($F = 6.7$, df $=$ 12, 26, $P = 0.001$) (Fig. 1C).

Cotton did not form fruit when treated with 2,4-D-dimethylammonium sprayed immediately or 7 days after harvest and shredding, while in other treatments the plants had 0.3–2.5 fruits per plant. The 2001–2002 tests showed that one application with 2,4-D-dimethylammonium (at 0 or 7 DAH) after harvest and shredding cotton provided the best control of live cotton stalks, but not all of the plants were killed. Results in 2003 showed that a second application of 2,4-D-dimethylammonium at 14 or 21 DAH provided near 100% control of regrowth cotton. The visual rating of these treatments was between 1 and 2, and significantly better than in other treatments ($F = 16.8$, df $= 11$, 124, $P = 0.001$) (Table 4).

The root mortality in treatments with a second application of 2,4-D-dimethylammonium at 14 or 21 DAH ranged from 95.0 to 100% ($F = 18.9$, df $= 11$, 124, $P = 0.001$). A significant reduction in regrowth cotton also was observed in treatments where the cotton was sprayed initially with dicamba-diolamine at 0 or 7 DAH followed by a treatment with 2,4-D-dimethylammonium after 28 days. Adding carfentrazone-ethyl to 2,4-D-dimethylammonium did not increase the efficacy of herbicide used but only accelerated manifestation of reaction to herbicides.

Table 4. Response (±SE) to herbicides and application timings in chemical cotton stalk termination field trials (2003)[a,b]

Treatment[c]	Plant ratings[d]	Percentage[d] root mortality
2,4-D (0 DAH)	2.2 (±0.2) bc	72.0 (±3.9) c
2,4-D (0 and 14 DAH)	1.4 (±0.1) d	95.0 (±2.2) ab
2,4-D (0 and 21 DAH)	1.1 (±0.1) d	100 a
2,4-D (0 and 28 DAH)	1.9 (±0.2) c	86.0 (±3.7) b
2,4-D + carfentrazone-ethyl (7 DAH)	2.8 (±0.1) b	70.0 (±3.9) c
2,4-D + carfentrazone-ethyl (0 and 7 DAH)	1.8 (±0.2) c	85.0 (±2.7) bc
2,4-D + carfentrazone-ethyl (0 and 14 DAH)	1.2 (±0.1) d	97.0 (±2.1) a
Dicamba (0 DAH)	3.0 (±0.2) b	60.3 (±4.2) c
Dicamba (0 and 28 DAH)	1.6 (±0.2) cd	85.7 (±3.3) b
Dicamba (7 DAH)	2.9 (±0.3) b	58.5 (±2.7) c
Dicamba (7 and 28 DAH)	1.2 (±0.1) d	100 a
Control	4.6 (±0.2) a	11.2 (±0.2) d

[a] Means within a column followed by the same letter are not significantly different (Tukey honestly significant difference, $P \leq 0.05$).
[b] All second treatments were with 2,4-D.
[c] DAH - days after harvest.
[d] Plant ratings and root mortality were checked 2 months after harvest.

While a second application of herbicide adds to the cost of control, this application can serve multiple purposes and would likely be necessary even if regrowth were eliminated with the first application. In addition to providing added control of regrowth, the second application should provide excellent control of volunteer cotton seedlings which would not be present at the time of the first application, as well as killing any surviving regrowth. A second application also could include additional or alternative herbicides to provide weed control.

Similarly to the present results, Livingston *et al.*[16] showed that, for shredded stalks treated with 1.0 or 1.5 lb acre^{-1} rates of 2,4-D-dimethylammonium, regrowth was suppressed over a 28–35 day period and cotton plants did not become capable of supporting boll weevil reproduction. The alternative products they tested provided only 30–50% suppression resulting from 1.0–1.5 lb acre^{-1} of 2,4-D-dimethylammonium applied immediately following shredding. Studies by Lemon *et al*[15] conducted in central Texas and Arkansas demonstrated that 2,4-D ester and amine formulations applied at 1.5 lb acre^{-1} provided the best overall performance, while dicamba-diolamine and thifensulfuron-methyl + tribenuron-methyl showed the least regrowth control.

The last of the present field studies also investigated the influence of herbicide applications to shredded versus standing cotton stalks after picker and stripper harvest. Prior to this research it was believed that stalks may require shredding (15–20 cm) for effective control, and previous results obtained by the present authors had shown greatly improved efficacy for shredded stalks following picker-harvested cotton. However, some growers in the Coastal Bend had been treating standing stalks and reporting excellent results. A study by Lemon *et al.*[15] confirmed the producers' experience. They showed that picker-harvested standing stalks can be more effectively destroyed with 2,4-D-dimethylammonium than stripper-harvested standing stalks. In the present studies, non-treated plots with standing cotton after stripper and picker harvest, or plots with immediately shredded cotton after harvest, did not suppress regrowth (plants were visually rated as healthy, dead roots were 12.8–36.7% and plants contained numerous fruit) (Figs 2A, B and C). However, when sprayed with 2,4-D-dimethylammonium immediately after harvest, regrowth cotton control in standing stripper-harvested cotton was significantly more effective than for standing picker-harvested cotton ($F = 140.9$, df = 8, 303, $P = 0.001$) (Fig. 2A). Root mortality of cotton spayed with 2,4-D-dimethylammonium immediately after harvest was significantly higher for standing stripper-harvested cotton compared with standing picker-harvested cotton ($F = 88.1$, df = 8, 153, $P = 0.001$) (Fig. 2B). Stripper harvesting caused more wounds and abrasions to the cotton plants than picker harvesting. Presumably, this contributed to more and faster penetration of herbicides into the plants and increased their efficacy, as was observed with shredding. After treatment with 2,4-D-dimethylammonium (0 days), the standing picker-harvested cotton contained 0.03 fruits per plant, while standing stripper-harvested cotton did not form any fruit. When shredded cotton was sprayed with 2,4-D-dimethylammonium once, immediately after harvest, all vegetative indices were significantly better than in standing cotton (plant rating was 1.425, root mortality was 87.8% and 0 fruit per plant). In this experiment, the best results were obtained when standing (stripper- and picker-harvested) or shredded cotton was sprayed with 2,4-D amine twice, at 0 and 14 days after cotton was harvested, and no significant differences were observed between these treatments.

Both ground reflectance spectra and airborne digital imagery were used to separate regrowth differences among the six treatments. Ground reflectance spectra were able visually to separate regrowth differences among the treatments. Although the airborne imagery did not provide sufficient visual differences among the treatments because of the limited amount of regrowth when the imagery was taken, the spectral information extracted from the imagery allowed quantitative comparisons among the treatments. Table 5 shows the multiple comparison results for the green band and the near-infrared (NIR)/green band ratio as compared with the ground visual rating. Both the green band and the band ratio were able to detect significant differences among the six treatments. Treatments 1, 2 and 4 had more regrowth than treatments 3, 5 and 6. Statistical results showed that, with the use of vegetation indices, it was possible to differentiate among the treatments. These results generally agreed well with the ground observation results for these experiments (Table 5). Remote sensing technology can be a useful tool for evaluating herbicide-based regrowth control strategies for cotton stalk destruction. If a large number of treatments are to be evaluated over large areas, this technique can reduce the time

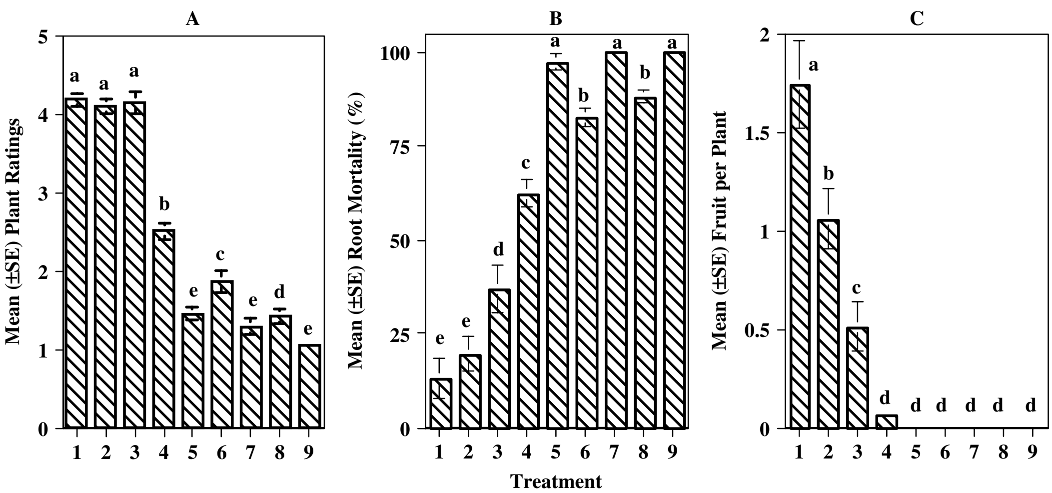

Figure 2. Effects of 2,4-D-dimethylammoniuim on stalk termination of shredded or standing cotton after picker or stripper harvesting. Different letters on the bars indicate significant differences, Tukey HSD ($P \leq 0.05$) (2004): **A** indexed by visual plant ratings 1–5 (1 = no plant alive, 5 = most plants appear healthy); **B** indexed by root mortality and fruit per plant of shredded or standing picker- or stripper-harvested cotton; **C** indexed by fruit per plant of shredded or standing picker- or stripper-harvested cotton; **1** picker-harvested standing cotton; **2** stripper-harvested standing cotton; **3** shredded immediately after harvest (0 days); **4** picker-harvested standing cotton, 2,4-D (0 days); **5** picker-harvested standing cotton, 2,4-D (0 and 14 days); **6** stripper-harvested standing cotton, 2,4-D (0 days); **7** stripper-harvested standing cotton, 2,4-D (0 and 14 days); **8** shredded cotton, 2,4-D (0 days); **9** shredded cotton, 2,4-D (0 and 14 days).

Table 5. Comparison of remote sensing method and visual rating method among six herbicides treatments for cotton stalk destruction (±SE) (2003)[a]

Treatment[b]	Green band[c]	NIR/green[d]	Visual rating
2,4-D (0 days)	7.6 (±0.6) ab	2.8 (±0.2) ab	2.4 (±0.4) ab
2,4-D (7 days)	7.4 (±0.7) a	2.9 (±0.2) a	2.6 (±0.8) a
2,4-D (0 and 14 days)	8.3 (±0.2) cd	2.4 (±0.1) cd	1.4 (±0.4) cd
2,4-D (0 + 28 days)	8.0 (±0.5) bc	2.7 (±0.2) b	2.1 (±0.7) abc
2,4-D + carfentrazone-ethyl (0 and 7 days)	8.2 (±0.3) cd	2.5 (±0.1) c	1.8 (±0.3) bcd
2,4-D + carfentrazone-ethyl (0 and 14 days)	8.5 (±0.4) d	2.4 (±0.2) d	1.2 (±0.5) d

[a] Means within a column followed by the same letter are not significantly different (Tukey honestly significant difference, $P < 0.05$).
[b] Days after harvesting and shredding in parentheses.
[c] Percent reflectance in the green band (555–565 nm) of airborne imagery.
[d] Reflectance ratio between the near-infrared (NIR) band (845–857 nm) and the green band (555–565 nm) of airborne imagery.

and labor cost for accurate and objective assessments of various regrowth control treatments.

The present tests have shown the potential efficacy of chemical stalk destruction for boll weevil management. Of the products tested, 2, 4-D-dimethylammonium has shown the greatest potential for preventing regrowth and fruiting in cotton, thereby preventing boll weevil reproduction. Development of efficacious chemical stalk destruction methodology should greatly improve boll weevil management in the LRGV of Texas, as well as other locations where year-round cotton growth and reproduction present a severe challenge for boll weevil management. While mechanical stalk destruction will continue to play an important role in cotton regrowth and boll weevil management, chemical-based stalk destruction offers a valuable tool for use in a variety of situations where mechanical stalk destruction is undesirable, inadequate or ineffective. This tool should greatly aid the establishment and maintenance of a host-free period for boll weevil management in tropical and subtropical environments.

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